Metrics and Benchmarks for Energy Efficiency in Laboratories

Paul Mathew, Ph.D., Steve Greenberg, P.E., Dale Sartor, P.E.,
Lawrence Berkeley National Laboratory

Peter Rumsey, P.E., John Weale, P.E.
Rumsey Engineers

1 Introduction

A wide spectrum of laboratory owners, ranging from universities to federal agencies, have explicit goals for energy efficiency in their facilities. For example, the Energy Policy Act of 2005 (EPACT 2005) requires all new federal buildings to exceed ASHRAE 90.1-2004 [1] by at least 30%. A new laboratory is much more likely to meet energy efficiency goals if quantitative metrics and targets are specified in programming documents and tracked during the course of the delivery process. If not, any additional capital costs or design time associated with attaining higher efficiencies can be difficult to justify.

This article describes key energy efficiency metrics and benchmarks for laboratories, which have been developed and applied to several laboratory buildings – both for design and operation. In addition to traditional whole building energy use metrics (e.g. BTU/ft^2.yr, kWh/m^2.yr), the article describes HVAC system metrics (e.g. ventilation W/cfm, W/L.s^{-1}), which can be used to identify the presence or absence of energy features and opportunities during design and operation.

Definitions:

Metric: a unit of measure that can be used to assess a facility, system or component; e.g. Ventilation W/cfm (W/L.s^{-1}).

Benchmark: a particular value of a metric that denotes a level of performance; e.g. 0.6 W/cfm (1.2 W/L.s^{-1}) represents a "good practice" benchmark.

2 Whole Building Metrics

2.1 Applying ASHRAE 90.1 to Labs

ASHRAE Standard 90.1 is increasingly being used as a benchmark for new construction, especially those projects seeking a LEED rating. Typically this involves setting goals relative to the performance of a baseline building, as defined in the standard. In practice however, simply specifying a goal of "x% better than ASHRAE 90.1" is inadequate for laboratories, because it leaves several key factors open to interpretation, which in turn will affect the meaning of the percentage reduction goals.

The Laboratories for the 21st Century Program (Labs21) has developed modeling guidelines [2] which clarify or modify selected sections of the ASHRAE 90.1 standard in order to make them more applicable to systems serving laboratory spaces, as summarized in Table 1. While the Labs21 guidelines are designed to be used in conjunction with Appendix G of the standard, they were developed by Labs21 and are not officially a part of the standard. However, it is anticipated that most of the key provisions will be incorporated into the standard through the "continuous maintenance" process. As of this writing, the fan power limitation has been addressed through

Addendum ac, which will be incorporated into the 2007 version of the standard. To the extent that other elements in the guidelines are not yet part of the standard, it is recommended that they be followed when modeling laboratory buildings.

Table 1 Issues addressed by the Labs21 Modeling Guidelines

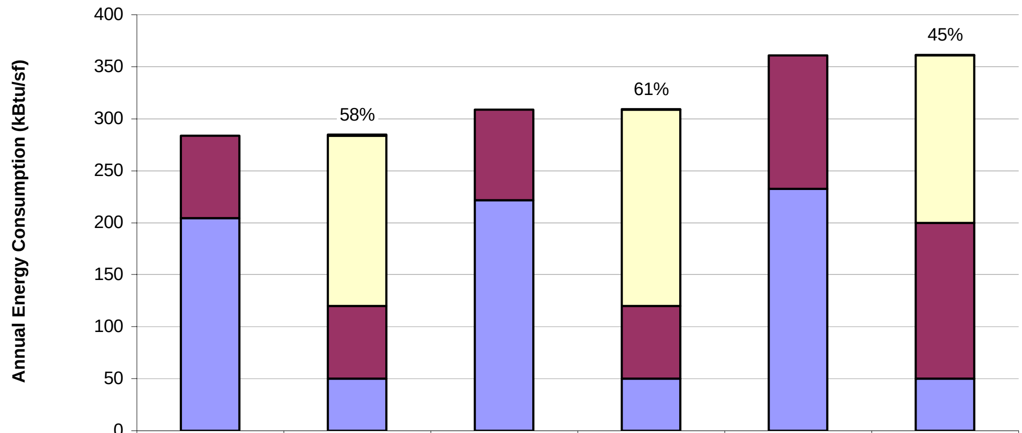
Guideline Area	*ASHRAE 90.1 sections addressed*	*Intent and rationale for modification*
I. Baseline HVAC system type and energy recovery	6.5.7.2 Fume Hoods G3.1.1 Baseline HVAC System Type and Description Table G3.1.1A Baseline HVAC System Types G3.1.2.10 Exhaust Air Energy Recovery	Clarify that a baseline building must have either a VAV system OR energy recovery, but not both. This provision applies to all laboratory air handling systems, not just systems serving fumehoods.
II. Laboratory fan power limitation	6.5.3.1 Fan Power Limitation G3.1.2.9 Fan Power	Increase the allowable fan power limitations. While the standard provides pressure credits for filtering systems, heat recovery, etc., laboratory fan systems typically exceed the fan limitations even with these credits.
III. Modeling load diversity and reheat energy impacts	Table G3.1 No.4 Schedules (new) G3.1.3.16 Supply-Air-to-Room Air Temperature Difference	Ensure that reheat energy use due to internal equipment load variations is properly modeled. Labs have large variations of internal equipment loads from one space to the next – this has a substantial impact on reheat energy use.

<u>Basis for % reduction:</u> There are two commonly used ways to express % reduction:

1. % reduction relative to total loads (including process loads)
2. % reduction relative to 'regulated loads' (excluding process loads)

Appendix G of the 2004 version specifies the first approach (i.e. based on total loads). Earlier versions of LEED-NC (prior to 2.2) followed the second approach. This often created confusion about what was included or excluded in the percentage calculation, and was especially problematic in laboratory buildings. For example, fumehoods were sometimes included because they are part of the HVAC system, and other times excluded because they were considered a process load. Figure 1 compares different options for calculating % reduction for the Science and Technology Facility at the National Renewable Energy Laboratory, which received a LEED-NC Platinum rating. The difference between the options underscores the need to clearly define how it is calculated and compared with other facilities [3].

While % reduction of total load is the primary metric that should be used, it is also useful to track % reduction of regulated loads, since it provides a measure of the efficiency of features that designers have significant control over. This is particularly true in laboratories, where process loads can vary significantly across different projects and design estimates are often grossly inaccurate.



	Budget Model (90.1-1999 ECB)	Proposed Model (90.1-1999 ECB) & Savings	Budget Model (Labs21 1999 ECB)	Proposed Model (Labs21 1999 ECB) & Savings	Baseline Model (90.1-2004 App. G)	Proposed Model (90.1-2004 App. G) & Savings
Savings %		58%		61%		45%
Savings	0	164	0	188	0	161
Electricity	80	70	87	70	128	150
Gas	204	50	222	50	233	50

Figure 1. Different options to calculate % reduction – results for the Science and Technology Facility at the National Renewable Energy Laboratory [3].

2.2 Metrics based on empirical performance

While metrics and benchmarks based on ASHRAE 90.1 are useful for exploring design alternatives, many owners and designers are uncomfortable with the wide variability in modeling results. Therefore whole building targets should be evaluated against empirical benchmarks that are based on the actual measured energy use of comparable buildings. For example, the energy goals for a new laboratory at Lawrence Berkeley National Laboratory were benchmarked against other laboratories (see Figure 2) with similar climatic context and lab area ratio (ratio of area requiring 100% outside air to gross building area).

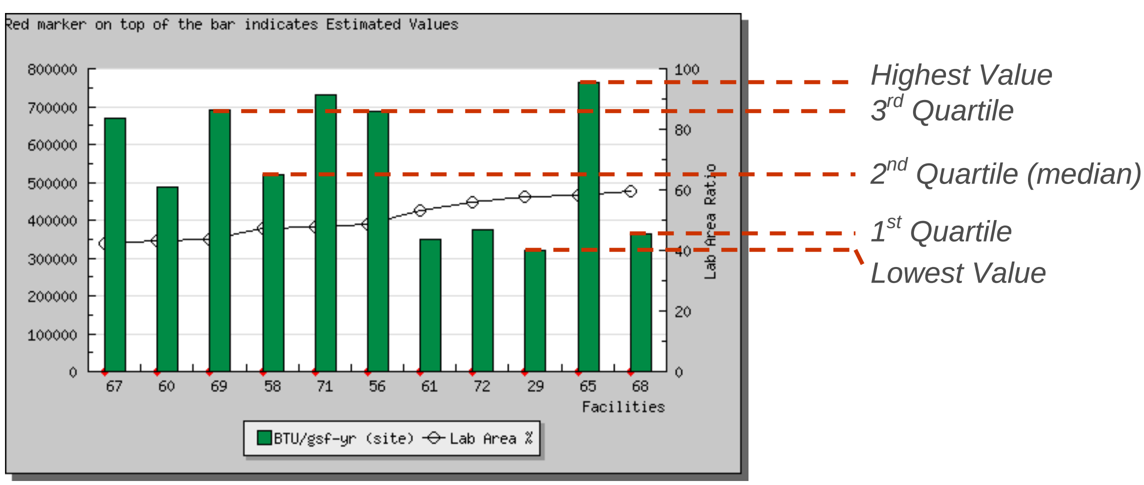


Figure 2. Empirical benchmarking data from Labs21 benchmarking database for laboratories with lab area ratio between 0.4-0.6 and located in the warm marine climate zone (e.g. San Francisco).

Whole building metrics discussed above are useful in assessing the overall efficiency level for a building. The remainder of this article describes HVAC system level metrics that can be used to identify specific opportunities for efficiency improvement.

3 Ventilation Metrics

3.1 Minimum required ventilation rate

Ventilation dominates energy use in most laboratories, especially chemical and biological laboratories. One of the key drivers of ventilation energy use is the minimum ventilation rate required for health and safety. The only exceptions to this are laboratories where the air change rates are driven by thermal loads (and hence always exceed minimum ventilation rates for health and safety) or where very high fume hood density, typically greater than 1 ft^2 (0.09 m^2) of hood work surface per 25 ft^2 (2.32 m^2) of laboratory, drives the minimum flow. The purpose of benchmarking minimum ventilation rates is to explore opportunities for optimization i.e. reducing air change rates while maintaining or improving safety. Air change rates should be benchmarked with two metrics:

<u>Air changes per hour (ACH)</u>: This is the most commonly used metric. Various standards and guidelines indicate that this can vary between 4 and 12 (Table 2), which is a very wide range. Values higher than 6 ACH (when occupied) and 4 ACH (unoccupied) may represent opportunities for optimization, or else should be justified as being required for health & safety.

Table 2 Air change rates recommended in various standards and selected projects [4]

Standard/Guideline	**Recommended Air Change Rate**
ANSI/AIHA Z9.5 [5]	The specific room ventilation rate shall be established or agreed upon by the owner or his/her designee.
NFPA-45-2004 [6]	Minimum 4 ACH unoccupied, occupied "typically greater than 8 ACH"
ACGIH Ind. Vent 24th Ed., 2001 [7]	The required ventilation depends on the generation rate and toxicity of the contaminant not on the size of the room in which it occurs.
ASHRAE Lab Guide-2001 [8]	4-12
OSHA 29 CFR Part 1910.1450 [9]	4-12
ASHRAE Standard 62.1-2007 [10]	Minimum ventilation rate in breathing zone (Table 6-1): 10 cfm/person (5 L/s.person) for laboratories in educational facilities.
Project	**Specified Air Change Rate**
UC Santa Cruz Bio-Med Building	6 ACH occupied, 4 ACH unoccupied
UC Davis Tahoe Center	6 ACH occupied, 4 ACH unoccupied in low risk labs
UC Berkeley Li-Kashing Building	6 ACH

CFM/sf (L/s.m²): Some laboratory professionals believe that this is a more appropriate metric, given that laboratory hazards are more related to floor area than volume i.e. a laboratory with a high ceiling does not necessarily require more ventilation. The International Building Code (2003) requires a rate of 1 cfm/ft² (5 L/s.m²) for H-5 hazard environments. Here again, values higher than this may represent opportunities for optimization.

3.2 Hood density

Fume hoods are prodigious consumers of energy and lab planners should work with owners to carefully avoid installing more and larger hoods than are necessary for programmatic requirements. Specifically, fume hoods should not be used for purposes that can be effectively met with lower-energy alternatives such as snorkels, balance hoods, and chemical storage cabinets. It is recommended that fumehood density should be benchmarked with other labs that have similar programmatic requirements. For example, Figure 3 shows the range of fumehood density (expressed as number of hoods/5000 gross square feet) in various laboratories in the University of California and California State University campuses. Based on this chart, values higher than about 3 hoods/5000 gsf (3 hoods/465 m²) may present opportunities for optimizing the number of fumehoods.

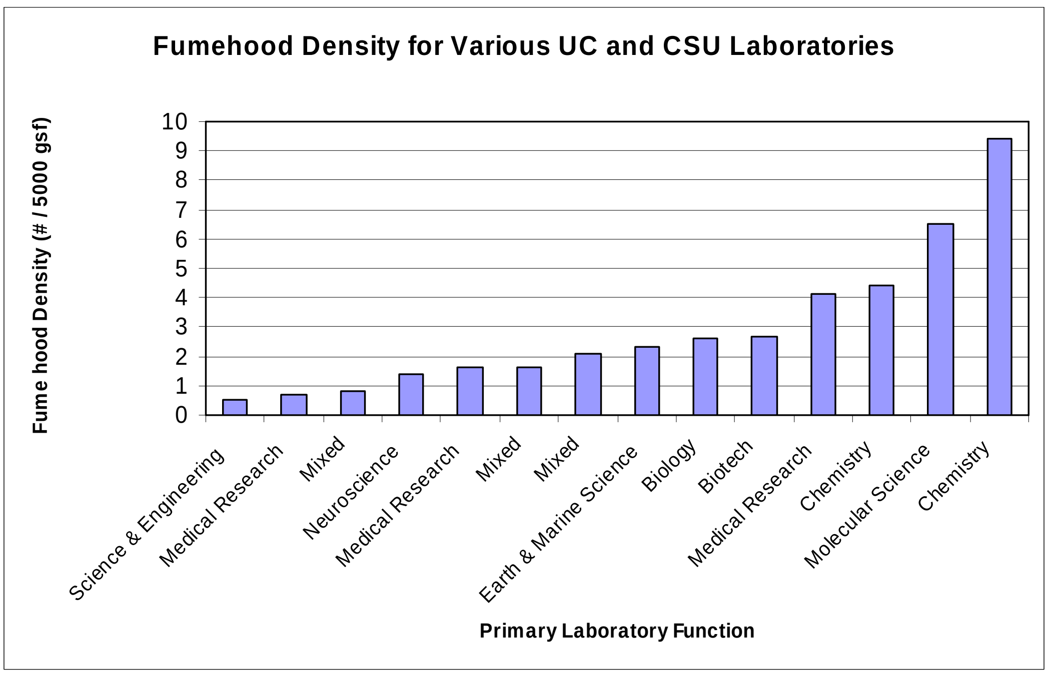


Figure 3 Fumehood density for selected academic laboratories across the University of California and California State University. Data source: UC/CSU/IOU Monitoring-based Commissioning Program.

3.3 Fume hood sash management

Once the number and size of fume hoods has been optimized, the next major opportunity is to reduce fume hood energy use by reducing airflow through low-volume fume hoods, and VAV hoods with effective sash management. While there are no commonly used metrics for sash management, we suggest using a metric such as fume hood airflow management ratio, defined as the ratio of the average flow to the minimum flow. Minimum flow is the flow through the fume hood when the sash is closed. For a typical 6-ft (1.8m) fume hood, this is usually about 300 cfm (142 L/s), which corresponds to the NFPA-45 mandated minimum of 25 cfm/ft² (125 L/s.m²) of work surface area. A typical 6-ft (1.8 m) fume hood with an 18” (46 cm) sash-stop operates at about 900 cfm (425 L/s). Therefore, if the sash were never closed, the airflow management ratio would be 3. If the sash were closed 50% of the time, the ratio would be 2.

Figure 4 shows the impact of sash management training on airflow management ratios for a laboratory at Duke University, indicating a significant improvement in sash management as a result of the training and awareness campaign.

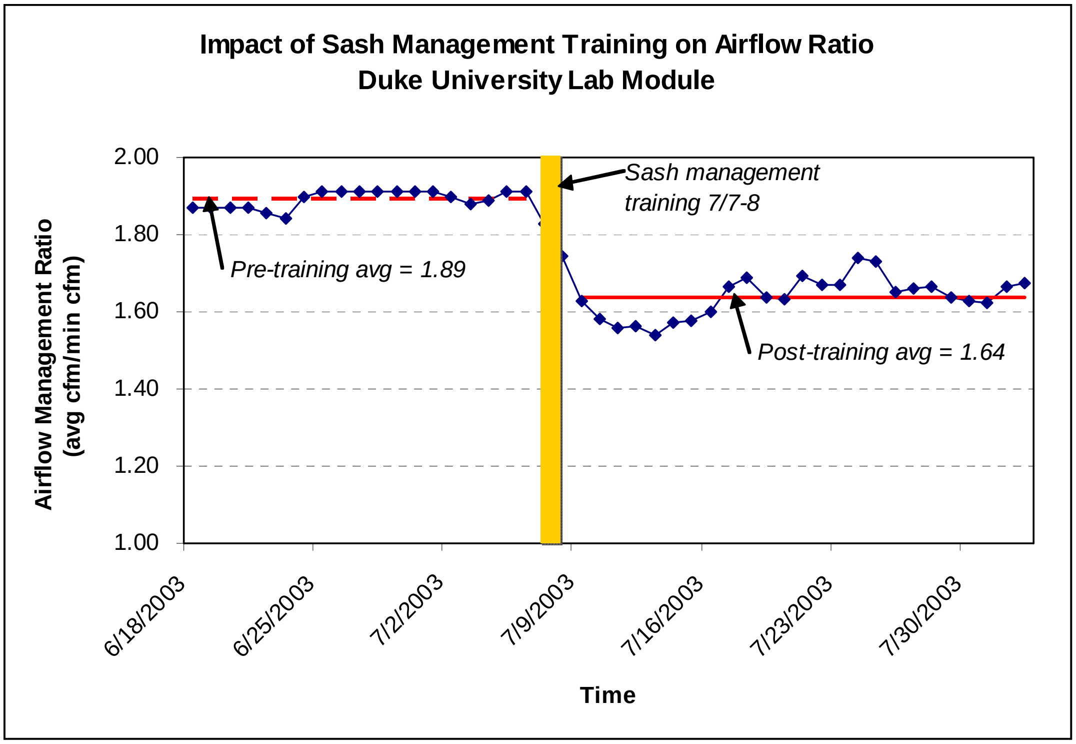


Figure 4 Impact of sash management training on airflow management ratios for a laboratory at Duke University. The airflow with sash open was 650 cfm (307 L/s), and with sash closed was 340 cfm (160 L/s). Therefore the airflow ratio if sashes were never closed would have been 1.91.

3.4 Ventilation air flow efficiency

Ventilation air flow efficiency is typically the most significant way that HVAC design engineers can influence overall lab efficiency. There are two key related metrics:

System pressure drop (in. w.g., Pa): Each component in the supply and exhaust system can be optimized for low pressure drop. Table 3 compares typical practice with low-pressure drop design for the Tahoe Center for Environmental Studies, which received a LEED Platinum rating. (Additional information on low-pressure drop benchmarks and design guidelines are described by Weale et al. [11] and Labs21 [12].)

Ventilation system W/cfm ($W/L.s^{-1}$): This metric is defined as the total power of supply and exhaust fans divided by the total cfm of supply and exhaust fans. It provides an overall measure of how efficiently air is moved through the laboratory, from inlet to exhaust, and takes into account low pressure drop design as well as fan system efficiency (motors, belts, drives). Figure 5 shows the range of ventilation system efficiency at peak loads for various laboratories in the Labs21 benchmarking database. There is a wide range of efficiencies, from 0.3 W/cfm ($0.6\ W/L.s^{-1}$) to 1.9 W/cfm ($3.8\ W/L.s^{-1}$). The fan power limitations specified in ASHRAE 90.1 2004 provide an additional benchmark.

Table 3 Comparison of typical and low-pressure drop design at the Tahoe Center for Environmental Studies at Sierra Nevada College.

	Typical	**TCES – UC Davis**
Air handling unit – Clean filters including system effect	2.2” w.g. (548 Pa)	0.68” w.g. (169 Pa)
Dirty Filter Allowance	1.3” w.g. (324 Pa)	1.45” w.g. (361 Pa)
Heat Recovery	0.5” w.g. (125 Pa)	0.56” w.g. (139 Pa)
Silencer	1.0” w.g. (249 Pa)	0
Supply Duct Work, Diffusers	2.5” w.g. (623 Pa)	0.65” w.g. (162 Pa)
VAV device	0.5” w.g. (125 Pa)	0.30” w.g. (75 Pa)
Zone coils	0.4” w.g. (100 Pa)	0.20” w.g. (50 Pa)
Safety Factor	0.6” w.g. (149 Pa)	0.60” w.g. (149 Pa)
Total Supply	**9.0” w.g. (2241 Pa)**	**4.4” w.g. (1096 Pa)**
Hood	0.50” w.g. (125 Pa)	0.50” w.g. (125 Pa)
Flow Device	0.45” w.g. (112 Pa)	0.30” w.g. (75 Pa)
Exhaust Duct Work	2.00” w.g. (498 Pa)	0.55” w.g. (137 Pa)
Heat Recovery with filter	0.50” w.g. (125 Pa)	0.50” w.g. (125 Pa)
Exhaust Outlet (incl. velocity pressure)	0.70” w.g. (174 Pa)	0.70” w.g. (174 Pa)
Total Exhaust	**4.15” w.g. (1033 Pa)**	**2.55” w.g. (635 Pa)**
Total Static Supply plus Exhaust	**13.15” w.g. (3275 Pa)**	**6.95” w.g. (1731 Pa)**

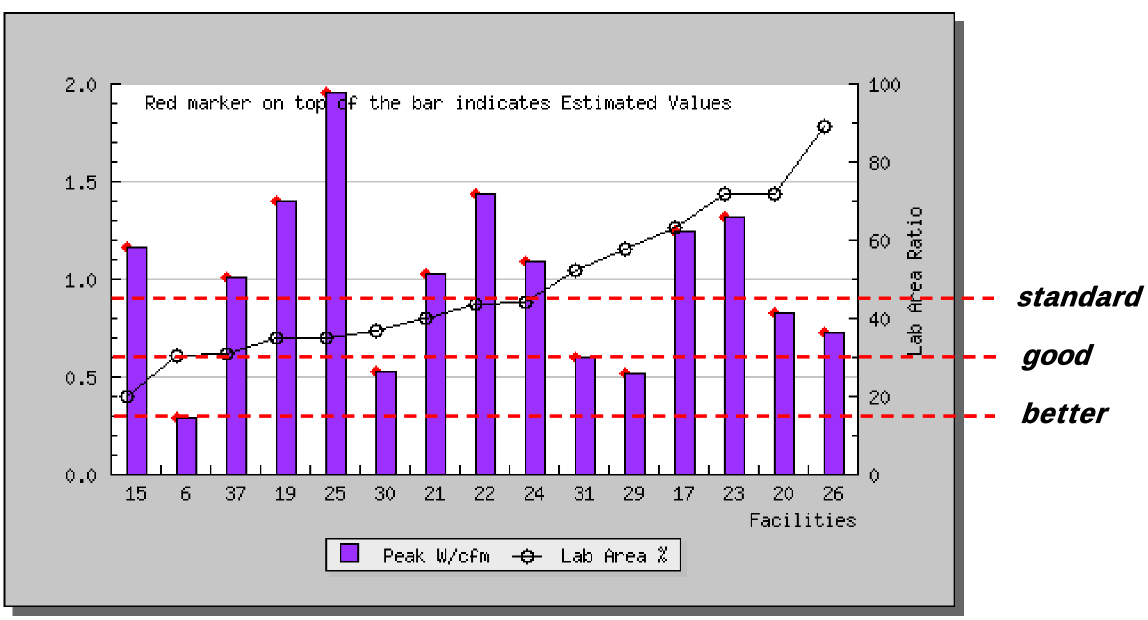


Figure 5 Ventilation system efficiency at peak conditions, for various laboratory facilities in the Labs21 energy benchmarking database. The benchmarks for standard, good and better practice are based on the Labs21 best practice guide on low pressure drop design [12].

4 Cooling and Heating Metrics – Special Considerations for Labs

4.1 Laboratory temperature and humidity set points

Temperature and humidity setpoints in laboratory spaces are driven by human comfort and laboratory function (experimentation/equipment requirements). Laboratory users and planners sometimes call for tight tolerances based on laboratory function, without evaluating whether these are actually required. Tight tolerances can increase energy use due to reheat and humidification. It is recommended that tolerances tighter than those required for human comfort (e.g. based on ASHRAE Standard 55 [13]), be carefully evaluated and explicitly justified. At the global ecology center at Stanford University, equipment requiring tight tolerances (70+/-1F, 21+/-0.5C) was grouped into a dedicated area, so that other areas of the lab could be controlled to wider tolerances (73+/-5F, 23+/-3C) with some rarely accessed freezers and growth chambers actually relocated to a minimally-conditioned adjacent structure controlled to 55 – 95F (13-35 C).

4.2 Heating and cooling system efficiency

The key metrics and benchmarks to evaluate the efficiency of chiller and boiler systems in labs are no different than those typically used in other commercial buildings. These include chiller plant efficiency (kW/ton), cooling load (tons/gsf, ton/m^2), boiler efficiency (%), pumping efficiency (hp/gpm, W/L.s^{-1}), etc. Since these are well-documented elsewhere, they are not discussed here. However, two additional metrics which have special impact on lab efficiency bear further discussion:

<u>Chiller system minimum turndown ratio</u>: Laboratory systems are often oversized due to reliability/redundancy requirements, over-estimated process loads, or other factors. Even when systems are "right-sized", there are many hours when loads are much lower than peak. Therefore, chiller systems in labs should be designed for low minimum turndown ratios, defined as the ratio of minimum load (with continuous compressor operation without hot gas bypass or other false loading methods) to design load. Standard practice would be about 20%. Good and better practice benchmarks would be 10% and 5% respectively. In the Molecular Foundry at Lawrence Berkeley National Laboratory, the chiller system is capable of a 5% turndown ratio. In labs with tight humidity control, even lower ratios are warranted, unless alternative dehumidification strategies are adopted.

<u>Reheat energy use factor</u>: Reheat energy use can be significant in labs. This can be due to tight temperature and humidity requirements, wide variation in loads served by a given air handling system [14], or poorly calibrated controls. While there is no well-established metric for assessing reheat energy use, we suggest a metric such as reheat energy use factor, defined as the ratio of the reheat energy use to the total space heating energy use. An alternative metric may be ratio of reheat design capacity to chiller design capacity. The best practice benchmark for this would be 0% (i.e. complete elimination of reheat energy use for temperature control). The Koshland Integrated Natural Science Center at Haverford College achieves this by using dual heat wheels and separation of thermal and ventilation systems [15].

5 Plug Load Metrics

Equipment loads in laboratories are frequently overestimated because designers often use estimates based on "nameplate" data, and design assumptions of high utilization. This results in oversized HVAC systems, increased initial construction costs, and increased energy use due to inefficiencies at low part-load operation [16]. The following related metrics can be used to assess and compare design and measured plug loads:

Laboratory design plug load W/sf (W/m²): The values may vary across lab spaces in a given building. Note that the assumption for electrical system design is usually higher than that for HVAC system design.

Laboratory actual (measured) plug load W/sf (W/m²): For a building currently in design, it is recommended that measurements be taken in a comparable laboratory and those data be used for sizing. This is obtained by taking continuous measurements at the panel serving laboratory plug loads. For HVAC system design, it is more appropriate to consider the maximum of the 15-minute interval averages (rather than maximum instantaneous load), since HVAC systems typically do not react to the instantaneous loads.

Figure 6 compares the measured peak loads (maximum instantaneous and maximum 15-min interval average) to the design loads for various laboratory spaces in a building at the University of California Davis. While the sizing ratio (design/measured) is driven by context specific factors such as reliability and flexibility, it is recommended that sizing ratios greater than 2 be carefully evaluated and justified.

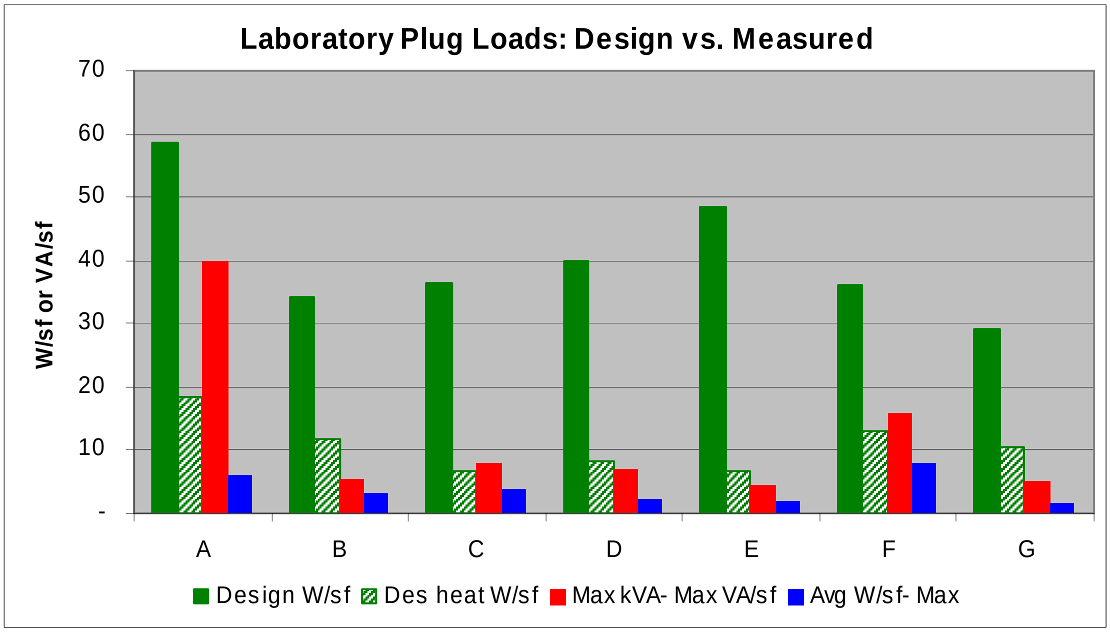


Figure 6 Comparison of design loads and measured plug loads in various laboratory spaces within a building at the University of California at Davis. Measurements were taken over a 2-week period while labs were fully occupied. Des W/sf is the peak plug load assumption for electrical design. Des heat W/sf is the peak plug load assumption for HVAC design. Max Apparent Power is the measured peak (instantaneous) apparent power. Max Interval Power is the maximum of the 15-minute averages.

6 Conclusion

Laboratories are much more likely to meet energy efficiency goals if quantitative metrics and targets are explicitly identified and tracked during the course of design, delivery and operation.

This article described key metrics and benchmarks at the whole building level as well as at the system level.

- While ASHRAE 90.1 can effectively be used as a basis for evaluating whole building performance, it is recommended that it be used in conjunction with all the most recent addenda as well as the Labs21 modeling guidelines to address some lab-specific issues such as equipment load diversity and fan power limitations.

- It is strongly recommended that whole building targets be evaluated against empirical benchmarks that are based on the measured energy use of peer facilities.
- Key ventilation system metrics include: minimum air change rate (ACH, cfm/sf, L/s.m^2), hood density (hoods/nsf, hoods/m^2), hood airflow efficiency, system airflow efficiency (W/cfm, W/L.s^{-1})..
- Heating and cooling system efficiency metrics for laboratories are not significantly different from those used for other commercial buildings, although there are some special considerations for laboratories.
- Design assumptions for plug loads should be benchmarked against measured values in comparable laboratories.

Metrics and benchmarks are in effect key performance indicators for the quality of design and operation. To ensure that they are effectively used, owners and designers should obtain the buy-in of all the key stakeholders, incorporate them into programming documents, and track them consistently during over the course of the design process.

Acknowledgements

This article was based on a best practice guide developed for the Laboratories for the 21st Century (Labs21) Program, a federal program sponsored by the U.S. Department of Energy and U.S. Environmental Protection Agency. This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

References

1. *ASHRAE/ANSI/IESNA Standard 90.1: Energy Standard for Buildings except Low-Rise Residential Buildings* . American Society of Heating, Refrigerating, and Air-Conditioning Engineers. Atlanta, Georgia.

2. Laboratory Modeling Guidelines using ASHRAE 90.1-2004 Appendix G. Available at: http://www.labs21century.gov/toolkit/bp_guide.htm

3. *Energy Modeling Analysis and Baseline Performance Comparison for NREL Science and Technology Facility and EPA Kansas City Science and Technology Center,* Prepared by National renewable Energy Laboratory and Architectural Energy Corporation for Labs21. August 2006.

4. Optimizing Ventilation Rates in Laboratories. Draft Best Practice Guide available from Labs21. (Contact GCBell@lbl.gov)

5. ANSI/AIHA Z9.5-2003. "American National Standard for Laboratory Ventilation", American National Standards Institute, Inc./ American Industrial Hygiene Association.

6. NFPA-45-2004. National Fire Protection Association.

7. ACGIH 2001. Industrial Ventilation: A Manual of Recommended Practice – 24th Edition. The American Conference of Governmental Industrial Hygienists, Inc. (ACGIH), eds. Cincinnati, OH. ISBN: 1-882417-42-9, 2001.

8. McIntosh, I. B. D., C. B. Dorgan, C. E. Dorgan [2001]. *ASHRAE Laboratory Design Guide,* American Society of Heating, Refrigerating, and Air-Conditioning Engineers. Atlanta GA.

9. OSHA 29 CFR 1919-1450 Appendix C. 1990. Occupational Safety and Health Administration

10. *ANSI/ ASHRAE Standard 62.1: Ventilation for Acceptable Indoor Air Quality.* American Society of Heating, Refrigerating, and Air-Conditioning Engineers. Atlanta, Georgia.
11. Weale, J., P. Rumsey, D. Sartor, L. E. Lock [2002]. "Laboratory Low-Pressure Drop Design," ASHRAE Journal, August, 2002.

12. *Low Pressure Drop Design for Laboratories,* published by Laboratories for the 21st Century Program. Available at: http://www.labs21century.gov/toolkit/bp_guide.htm

13. *ASHRAE/ANSI/IESNA Standard 55: Thermal Environmental Conditions for Human Occupancy.* American Society of Heating, Refrigerating, and Air-Conditioning Engineers. Atlanta, Georgia.

14. Mathew, P., S. Greenberg, D. Frenze, M. Morehead, D. Sartor, W. Starr. "Right-sizing Laboratory HVAC systems – Part 2," *HPAC Engineering*, October 2005.

15. Bartholomew, P. [2004]. "Saving Energy in Labs," *ASHRAE Journal*, February 2004. pp35-40.

16. Mathew, P., S. Greenberg, D. Frenze, M. Morehead, D. Sartor, W. Starr. "Right-sizing Laboratory HVAC systems – Part 1," *HPAC Engineering*, September 2005.